Credible Numbers: A Procedure for Reporting Statistical Precision in Parameter Estimates

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EEA-ESEM Annual Congress
-
27 August 2024

A simple example

Standard problem:

- Consider an econometrician who want to recover the "impact" of an explanatory variable X_1 on an outcome variable y, while observing other variables X_2 and X_3.
- Assume the econometrician has retrieved a sample of T observations of $(y_t, X_{1t}, X_{2t}, X_{3t})$ (where t indexes observations).

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Usually unknown information:

- The "true" relationship is:

$$y = 1 + 1.234X_1 + X_2 + X_3 + \epsilon$$

  where ϵ is a non-modelled error term.
- This sample has been generated by taking i.i.d. draws from the following distributions:

$$X_{1t} \sim \mathcal{N}(0,1),\ X_{2t} \sim \mathcal{N}(0,5),\ X_{3t} \sim \mathcal{N}(0,10),\text{ and } \epsilon_t \sim \mathcal{N}(0,5).$$

Current practice

- The econometrician specifies a handful of models:

Model 1: $y_t = \beta_0 + \beta_1 X_{1t} + \eta_{1t}$

Model 2: $y_t = \beta_0 + \beta_1 X_{1t} + \beta_2 X_{2t} + \eta_{2t}$

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- Results table for two different sample sizes:

	Model 1	Model 2	Model 3
X_1	1.174**	1.176**	1.104***
	(0.510)	(0.468)	(0.250)
X_2		0.864***	0.945***
		(0.196)	(0.105)
X_3			1.074***
			(0.069)
Constant	1.131**	1.204***	1.118***
	(0.459)	(0.422)	(0.225)
Observations	100	100	100
R^2	0.051	0.209	0.777

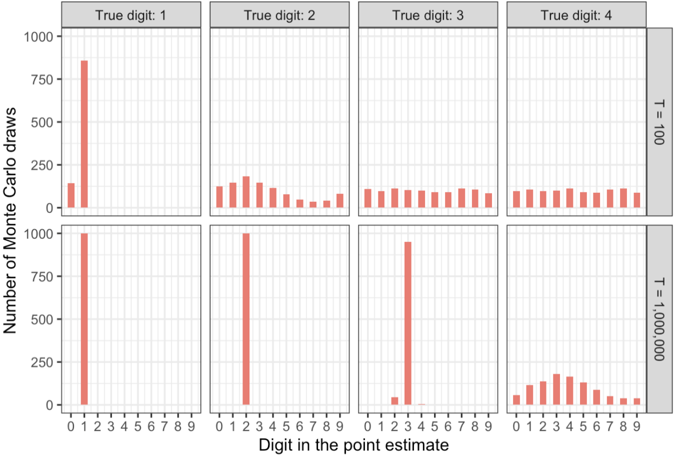
T = 100

	Model 1	Model 2	Model 3
X_1	1.237***	1.235***	1.234***
	(0.004)	(0.004)	(0.002)
X_2		0.999***	1.000***
		(0.002)	(0.001)
X_3			1.000***
			(0.001)
Constant	0.999***	0.999***	1.000***
	(0.004)	(0.004)	(0.002)
Observations	1,000,000	1,000,000	1,000,000
R^2	0.071	0.303	0.768

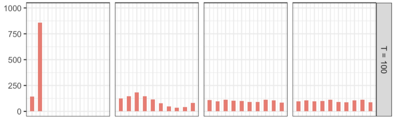
T = 1,000,000

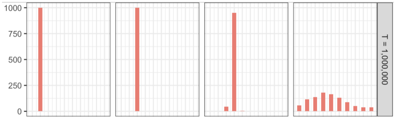
Actual precision - Monte Carlo simulation

Distributions of the digits of the coefficient $\hat{\beta}_1$ across 1,000 draws of datasets (Model 3).



A different approach?





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   ⇒ Yes: about 60% of the digits printed in the AER between 2000 and 2022 are not significant.

Outline

1. Some econometrics even I understand
2. Proposed reporting rule
3. Practical significance
4. Conclusion

Framework

- Let $\hat{\theta}$ be a scalar estimated from observed data by a researcher (e.g. a coefficient estimate).
- Being a finite real number, $\hat{\theta}$ can be decomposed as a series of digits $\{\hat{d}_i\}_{i=-\infty \dots D}$:

$$\hat{\theta} \equiv \sum_{i=-\infty}^{D} \hat{d}_i 10^i$$

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- In practice however, researchers only report a limited number of decimal digits. In other words, the "published" or "printed" value of $\hat{\theta}$, which we denote with $\hat{\theta}_p$, is:

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$$\hat{\theta}_p = \sum_{i=i_0}^{D} \hat{d}_i 10^i$$

- **Current practice:** pick a default value for i_0, usually -3.
- **Our proposal:** choose i_0 endogenously to somehow reflect the level of precision of the estimate.

Significant digits - Concept

- We propose to build on the literature on "equivalence testing" (Wellek, 2010).

- The objective of an equivalence test is to compare the following hypotheses:

$$H\colon\ \theta \leq a \text{ or } \theta \geq b \qquad \text{versus} \qquad K\colon\ \theta \in \,]a, b[$$

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- To assess whether digit $i = 0$ is significant, we test:

$$H^{i=0}\colon\ |\theta - 1.234| > 1 \qquad \text{versus} \qquad K^{i=0}\colon\ \theta \in]0.234, 2.234[$$

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- To assess whether digit $i = -1$ is significant, we test:

$$H^{i=-1}\colon\ |\theta - 1.234| > 0.1 \qquad \text{versus} \qquad K^{i=-1}\colon\ \theta \in\ ]1.134, 1.334[$$

Last significant digit

Definition (Last significant digit)

We define the rank $i^*(\alpha)$ of the "last significant digit" as the smallest value of i such that digit $\hat{d}_i$ is significant at level α:

$$i^*(\alpha) \equiv \min_i \{ i \mid \hat{d}_i \text{ is a significant digit at level } \alpha \}$$

Number of sizable digits

Equivalence testing

- Our definition of significant digits does not specify which equivalence test should be run.
- We propose to adopt the widely used "two one-sided test" (TOST).

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- We propose to adopt the widely used "two one-sided test" (TOST).
- This test rejects the null hypothesis H_0^i at the level α if, and only if, the two following standard one-sided tests reject their null hypothesis at the level α:

$$H_a^i\colon\ \theta = \hat{\theta} - 10^i \quad \text{versus} \quad K_a^i\colon\ \theta > \hat{\theta} - 10^i\ (\psi_{ia})$$

and

$$H_b^i\colon\ \theta = \hat{\theta} + 10^i \quad \text{versus} \quad K_b^i\colon\ \theta < \hat{\theta} + 10^i\ (\psi_{ib})$$

Application to standard OLS - Coefficient estimates

- Consider the standard normal linear conditional mean model:

$$y = X\beta + \epsilon \tag{1}$$

where the conditional distribution of ϵ given the matrix X is a multivariate normal $T \times 1$ vector with mean zero and covariance matrix $\sigma^2 I_T$.

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- The level α rank of the last significant digit for b_k is:

$$i^*(\alpha) = \lceil \frac{\ln(SE(b_k)) + \ln(t_{1-\alpha}(T-K))}{\ln(10)} \rceil \tag{2}$$

where $\lceil x \rceil$ denotes the ceiling of x.

- More generally, a widely applicable asymptotic approximation for the size α rank of the last significant digit is:

$$i^*_\infty(\alpha) = \lceil \frac{\ln(SE(b_k)) + \ln(Z_{1-\alpha})}{\ln(10)} \rceil \tag{3}$$

where $Z_{1-\alpha}$, the $1-\alpha$ percentile of a $\mathcal{N}(0,1)$ random variable.

Outline

Back to our example

- Let's go back to our simple example where the true relationship is:

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- We assume the researcher observes a sample of $T = 60$ observations of $(y_t, X_{1t}, X_{2t}, X_{3t})$ (where t indexes observations) that has been generated by taking i.i.d. draws from the following distributions:

$$X_{1t} \sim \mathcal{N}(0,1),\ X_{2t} \sim \mathcal{N}(0,5),\ X_{3t} \sim \mathcal{N}(0,10), \text{ and } \epsilon_t \sim \mathcal{N}(0,5).$$

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- We assume the researcher estimates and reports three models:

Model 1: $y = \beta_0 + \beta_1 X_1 + \epsilon$
Model 2: $y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \epsilon$
Model 3: $y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \epsilon$

Estimation results

Current approach to report estimation results:

	OLS results		
	Model 1	Model 2	Model 3
X_1	0.923	1.018	0.947
	(0.678)	(0.623)	(0.366)
X_2		0.899	1.005
		(0.260)	(0.153)
X_3			1.010
			(0.097)
Constant	0.945	0.710	0.840
	(0.579)	(0.536)	(0.315)
Observations	60	60	60
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X_1	0.9	1.0	0.9
	(0.68)	(0.62)	(0.37)
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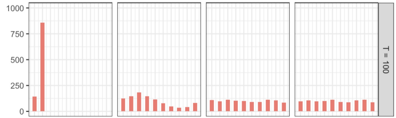
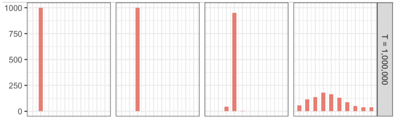
Removing non-significant digits:

- generally simplifies the presentation of results tables.
- attracts more attention to the magnitude of the estimates.
- makes statistical precision a salient attribute of estimates.

Scientific notations

Which digits are significant?





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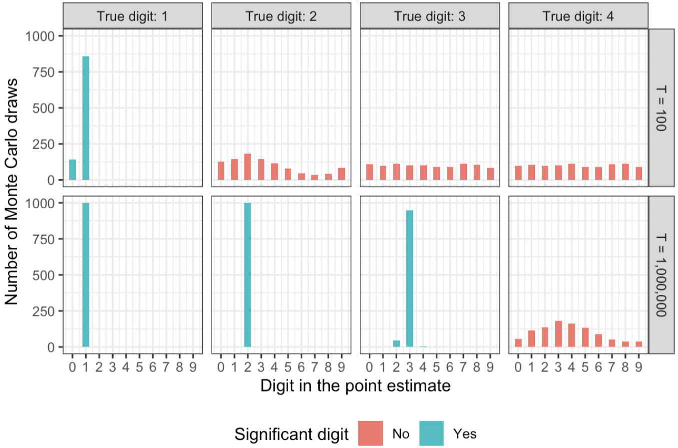

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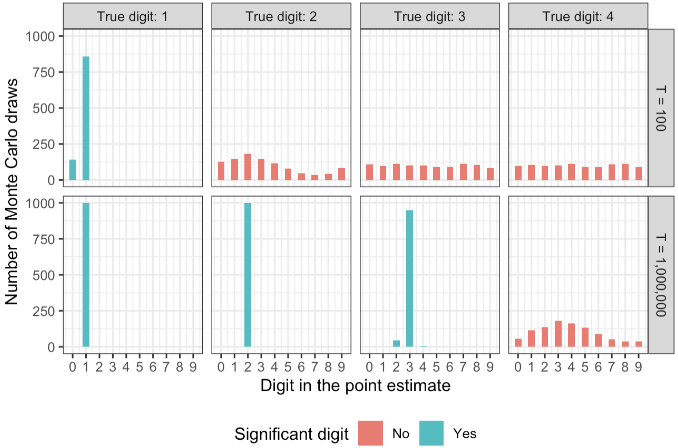

⇒ We propose that researchers should consider reporting digits only up to the first non-significant one.

Outline

Data collection

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- We obtain a dataset of over 90,000 pairs (coefficient, standard error), as reported in the published articles.
- We focus on coefficient estimates, for which a lower bound of the last significant digit can be built from the sole knowledge of the estimated standard error (asymptotic bound).

Number of reported decimal digits

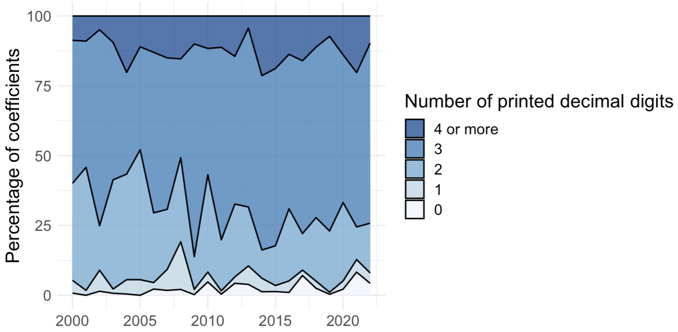

Figure: Number of decimal digits displayed for estimated coefficients.

Coefficients Standard errors

Main result (1/2)

Figure: Fraction of the printed digits of estimated coefficients that are not significant digits at different levels of statistical significance.

Main result (2/2)

Figure: Fraction of the printed digits of estimated coefficients that are not significant digits at different levels of statistical significance.

Number of sizable significant digits Robustness checks

Wrapping up

1. How can a researcher decide how many digits to report in coefficient estimates and standard error estimates?

   ⇒ We introduce a statistical concept of "significant digits" and propose to report estimates up to the first non-significant digit.

2. Would such a reporting rule be easy to implement?

   ⇒ Yes. It is for example embedded into the R package modelsummary.

3. Does current practice significantly depart from this reporting rule?

   ⇒ Yes: about 60% of the digits printed in the AER between 2000 and 2022 are not significant.

Thank you!

nicolas.astier@psemail.eu

Scientific notations

- The rank of the last significant digit may be a positive power of ten (e.g. $i^*(\alpha) = 2$).
- In such cases, the use of scientific notations would be warranted to avoid reporting non-significant zeros.
- Example: divide the units of X_1, X_2 and X_3 by 1,000

	OLS results		
	Model 1	Model 2	Model 3
X_1	9e+02	1.0e+03	9e+02
	(6.8e+02)	(6.2e+02)	(3.7e+02)
X_2		9e+02	1.0e+03
		(2.6e+02)	(1.5e+02)
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- Only occurs in a minority of cases in practice. Back

Distribution of coefficients

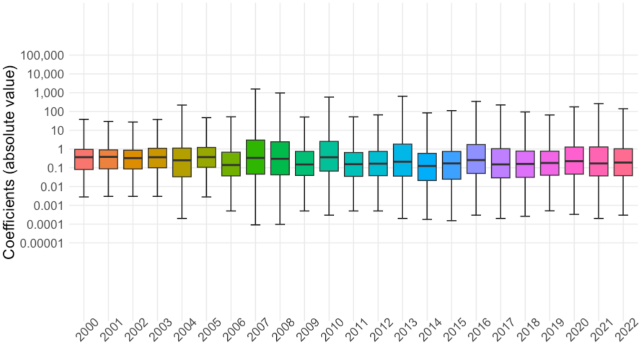

Figure: Box plots of the magnitude of estimated coefficients (absolute value in $\log_{10}$ scale). Boxes locate the first, second and third quartiles of the distributions. Top whiskers (resp. bottom whiskers) are drawn at a distance of 1.5 times the interquartile range above the third quartile (resp. below the first quartile).

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Distribution of standard errors

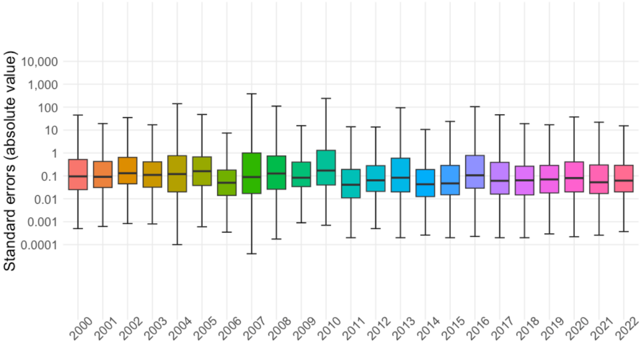

Figure: Box plots of the magnitude of estimated standard errors (absolute value in $\log_{10}$ scale). Boxes locate the first, second and third quartiles of the distributions. Top whiskers (resp. bottom whiskers) are drawn at a distance of 1.5 times the interquartile range above the third quartile (resp. below the first quartile).

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Robustness checks - Main concerns

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2. Main coefficient estimates may be more precisely estimated that the coefficients on control variables.

Robustness checks - Approach

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- The authors retrieved the estimated main effect and corresponding standard error from over 300 meta-analysis studies.
- We restrict the sample to general interest and field journals in economics.
- The resulting dataset consists of 18,000+ pairs of coefficient and their associated standard error estimates

Robustness checks - Results

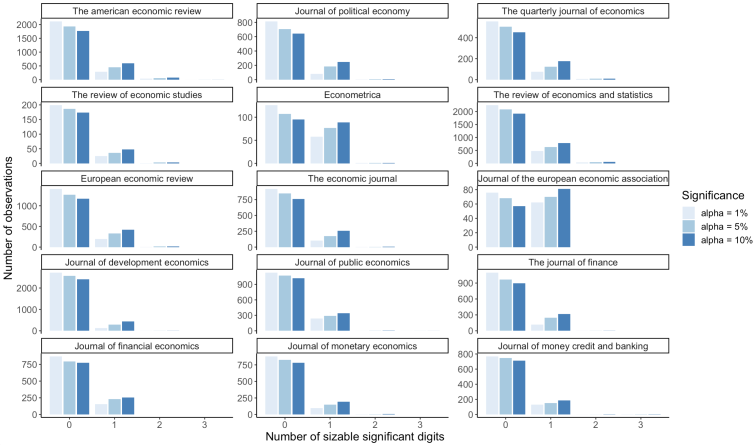

Figure: Histograms of the number of sizable significant digits for the different journals.

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Number of sizable significant digits

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Definition (Number of sizable significant digits)

Let $\hat{\theta} \equiv \sum_{i=-\infty}^{\infty} \hat{d}_i 10^i$ be an estimate of the scalar population parameter θ. Let $D(\hat{\theta})$ equal the largest rank of its non-zero digits:

$$D(\hat{\theta}) \equiv \max_i i\mathbf{1}\left[\hat{d}_i \neq 0\right] \tag{4}$$

Let $i^*(\alpha)$ equal the rank of the last significant digit of $\hat{\theta}$. We define the "number of sizable significant digits", $\nu(\alpha)$ as:

$$\nu(\alpha) \equiv \max(D(\hat{\theta}) - i^*(\alpha) + 1, 0)$$

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Main result - Other

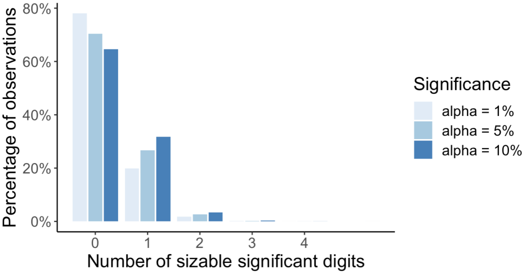

Figure: Distribution of the number of sizable significant digits.

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Prevalence of empirical work

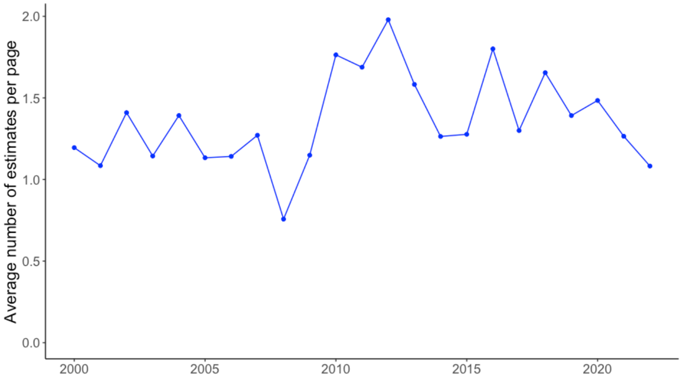

Figure: Evolution of the ratio of the number of reported empirical estimates in each year over the number of printed pages for that year.